

Work, Exercise and Space Flight

I. Operations, Environment, and Effects of Spaceflight

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This is a brief background of the physical realities of the current U. S. spaceflight program. The population of astronauts, their environment on earth and space, adaptation to this environment and effects of this adaptation are summarized. Companion papers which follow examine the effects of exercise on earth and in space and its use as a countermeasure to prevent undesired adaptations. The last paper describes means to make exercise in space possible.

Work and exercise have always played a significant role in spaceflight and will be crucial in extended flights of the future, possibly becoming the most important life sciences aspect of man in space. Work and exercise have already been important in the careers of astronaut candidates by the time of selection. While the role of physical fitness no longer plays the part it once did, very few unfit individuals are selected or remain in the program.

Population - There are two divisions of professional astronauts—pilots and mission specialists. The former are all male, active or ex-military operational pilots and usually test pilots. One does not survive in that environment without good neuromuscular, musculoskeletal, and cardiorespiratory capacity. Their NASA physical standards are essentially those of military pilots. (1) The second group is now far more diverse, especially as regards background. Medical standards for vision are somewhat reduced and there are essentially no size limitations, (2). The result is a significant range of physical characteristics and capacities in the astronaut population including:

Height: 5'2" (female) to 6'4" (male)

Weight: 100 lbs (female) to 210 lbs. (male)

Maximum O₂ intake: 30 to 60 ml kg⁻¹ min⁻¹
(mean 43 ml kg⁻¹ min⁻¹)

Strength: Unknown

The payload specialists and passengers are from an even more diverse background and have to meet considerably reduced physical standards (3,4).

While no physical performance standards are specified, the ubiquitous cardiorespiratory stress tests^a are given prior to acceptance and periodically thereafter with a few skin fold and respiratory studies. No formal attention is given to musculoskeletal performance or anthropometrics other than height and weight. We did a comprehensive musculoskeletal exam on the 200 astronaut candidates of 1978 which included complete anthropometrics and strength. NASA standards (5) are still extrapolated military anthropometric standards. Any task which depends upon strength or range of motion is usually done by cut and try. This lack of emphasis on the neuromusculoskeletal area has lead to some significant mistakes in the past and threatens to do so again.

Training - After selection, there is a candidate training program which involves flying as pilots or crewmembers in high-performance A/C, survival training, and other strenuous physical activities. It is at this point that astronaut physical training begins. Facilities are adequate with a well maintained gym with basketball, squash and handball courts, bicycle ergometers and rowing machines, weights, Nautilus, and other equipment. There is a good 1/4 mile outdoor track and plenty of roads and trails on site.

A point which always arises about this program is controlled versus uncontrolled physical training. I was surprised to arrive in 1967 and not find a rigid program but am now convinced that unstructured individual physical training is the only acceptable approach in this program. One of the best possible training programs has evolved in which everyone is responsible for his own well-being. This is one of the most competitive, individualistic, critical, and discerning groups to be found. While the researchers may argue over P and T's in exercise experiments, this group watches and listens to actual results where they happen. They know who can black them out pulling Gs in the T-38s, who can work 7 days, 80+

^aModified Bruce protocol.

hours a week and keep doing it, who walked off the spacecraft without trouble, and who was at work in the gymnasium after a spaceflight, and while they don't have statistical proof, they also know who is usually in the gym and what they do. When this group of competitive and motivated individuals see convincing evidence that exercise makes a difference, they become dedicated exercisers themselves. The individual results are frequently striking, e.g. a pear-shaped professor becoming a successful marathoner.

Next is the variety of exercise. The astronauts are also perceptive enough to select what works for them and what they can live with. What they can live with insures it will be continued. There are now many 'trainers' in the program. If you want to run, there are joggers, sprinters, and marathoners who know theory and practice, swimmers, weight lifters, and so on. The physicians in the office take fitness seriously in theory and practice. In short, it becomes a way of life for almost everyone in the office, and while no two individuals' programs are the same, they're near optimum for the tasks they must do. The astronaut's responsibility is to be fit enough to do his job, not standardized enough to fit an investigator's statistical requirements for publication. In this situation, the investigator must be capable of unobtrusively measuring and accounting for individual differences, not try to hammer them out. The misapplication of "standard

protocols" to individuals with unknown capacities has been a major source of error in exercise work in space and on earth. Anyone in the Astronaut Office will do whatever is assigned; and if there is a reason to have someone or a group on a standardized program, it can be done, but not indiscriminately nor routinely.

In addition to maintaining good physical condition, there are many other aspects of training for spaceflight. One must survive psychological pressures which are typically the largest stressor. There is frequent travel, often in T-38s, all over the country at all hours of day and night and one must frequently eat what and when it is available. There are training sessions and conferences and last minute changes which may last 16 hours a day or more. The media and public demands add to the load. One also tries to maintain a home and family. The majority are type A. In spite of this regimen, they typically launch in the best physical condition of their life.

Flight - As to physical demands of the launch, there is always the possibility of trying to escape from 200 feet up the pad, fighting fire as you go to the slide wires, to a rough landing and evacuation of the escape cars. One must also be able to evacuate the Shuttle after a crash landing by hauling one's own weight over the top [Fig. 1] or swinging off a bar to the ground some 10 ft. below. [Fig. 2].

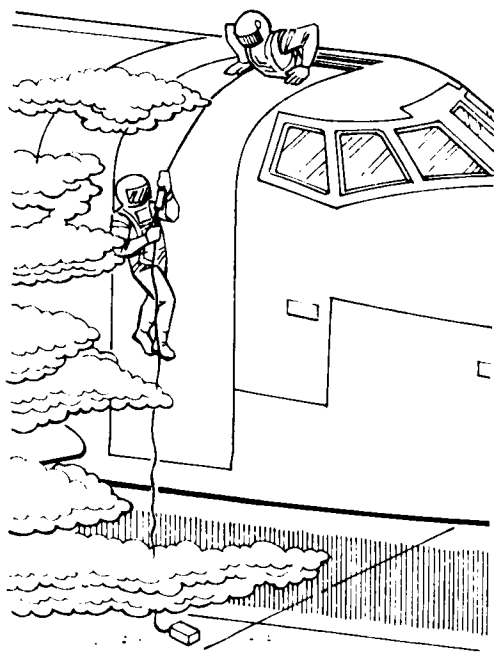


Fig. 1.- Secondary emergency egress from Shuttle. Crew lower themselves by a friction device on cable.

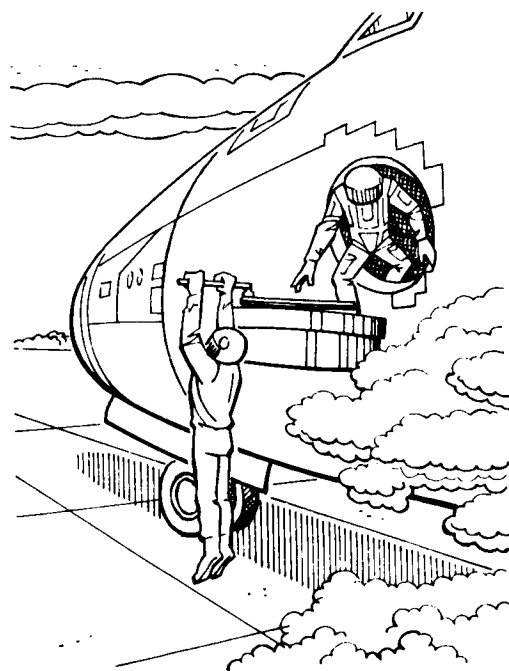


Fig. 2.- Primary emergency egress route from Shuttle. Distance between bar and ground is 10 feet. In every case, crewmen would wear emergency breathing gear.

Launch loads are modest with only +3.0 Gx and -0.6 Gz for the last minute. On orbit, the problem becomes one of keeping up with a usually jammed schedule which is busiest for the first two days and the time before entry and keeping up with a schedule which may, and often does, change from minute to minute. Food and sleep become secondary. Accommodations are limited—all decks are usually crowded with operational gear. The flight deck is occupied by 2 seats and controls, aft flight deck is ~3.5' L × 6.5' W × 6.1' H and middeck is 7.3' L × 11.5' W × 6.9' H. Hygiene is wash cloth or wet wipes, soap, and towel. Food is dehydrated in a myriad of plastic packages, wrappers, and appurtenances with some 'wet pack' items and a few fresh items provided for the first days. Atmosphere is composed of ppO₂ of 2.95-3.45 psi (~20%) and ppN₂ sufficient to maintain total pressure of 14.7 ± 0.2 psia. Carbon dioxide is maintained below 7.6 mmHg by LiOH scrubbing. The atmosphere is also scrubbed by activated charcoal for odor and trace contaminant control. Temperature may be selected between 65 to 80 ± 2°F. Relative humidity is typically 50% or less.

EVA operations are a class unto themselves and will be discussed by Dr. Moore. Suited operations have special physical requirements. The majority of the external loads are inertial, Force = Mass Acceleration. The largest masses may be moved by small but continued forces, however, the real problem is control both in direction and rate. Another common type of force is resistive (in terms of physics) such as repetitive motions in screwing on nuts or operating manual actuators. To date there have been no unsuited operations which require large forces nor high metabolic loads, i.e. it is a lazy environment on orbit.

On return, G-loads are +1.5Gz max. (eyeballs down) and small in terms of the normal body, but seem very large to a body adapted to weightlessness producing perceived loads of several times that. After landing unless one has prepared for it, one usually does not get out of the seat on the first attempt. In the event of an emergency, the crew could be forced to lift their body weight plus emergency breathing gear out the top hatch or swing to the ground 10 feet below from a bar on the side hatch. Such nominal emergency procedures could be complicated by incapacitated cohorts or poisonous fumes from damaged fuel tanks. The latter could require rapid locomotion for hundreds of yards or more. Immediately post landing, the perceived loads of walking are initially very large, say 2.0-3.0 G equivalent but adaptation rapidly occurs such that everyone to date has walked down the steps into the van, albeit sometimes after a period to allow recovery. Unusual weight and balance sensations occur over the next 24-36 hours.

This has been a very brief description of Shuttle operations, and there is a description of Space Station elsewhere in the report; however, Shuttle will be the transport for that operation.

Orbital Environment - Space is characterized by absence of the usual sustainers of life which must be provided by the spacecraft, i.e. atmosphere, food, water, etc. Above the atmosphere the Sun's full spectrum of electromagnetic radiation is received from X-rays to far infrared with a moderate (~40%) increase over the midday visible light intensity on earth. All potentially damaging radiation is shielded or attenuated to reasonable levels by the spacecraft windows or suit helmets. The earth's magnetic field deflects and shields us from virtually all particulate radiation but great quantities are trapped in the Van Allen belts high above our usual flight level. Other than during solar storms, radiation is not a concern with a mean value of 50 m Rem dose per mission.

While current spacecraft make travel possible, their orbital mechanics provide the major challenge to man in space for long periods—weightlessness—i.e. the centrifugal force almost exactly balances gravitational force. It has become chic to speak of 'microgravity' but this is a misnomer since in earth orbit gravity is typically reduced by only a small fraction over that at the earth's surface. The very small amount of unbalanced weight ("microweight") is of no practical concern to our problem.

Adaptation to weightlessness: The effects of weightlessness are now our primary concern in long-duration^a space flight. While these effects cascade through the body system producing higher and higher order effects, e.g. changes in heart rate or a hormone level, too often these are confused with the primary effects. The primary effects of weightlessness must be carefully considered for if not understood, counter-measures may be improperly chosen.

Effects of adaptation were initially manifest on post flight observation. The first objectively studied problem was weight loss [Fig. 3]. Even on short flights weight loss was largely regained within hours after return to 1g (6). Space motion sickness was experienced on the second manned flight by Titov (7). Orthostatic hypotension was often seen after flights of a few days (8). There was a reduction in cardio-respiratory capacity on flights of 1-2 weeks [Fig. 4] (9).

^aLong distance spaceflight simply translates into long duration. The physical effects of a current flight to Mars and return would be equivalent to an ±3-year stay in earth orbit.

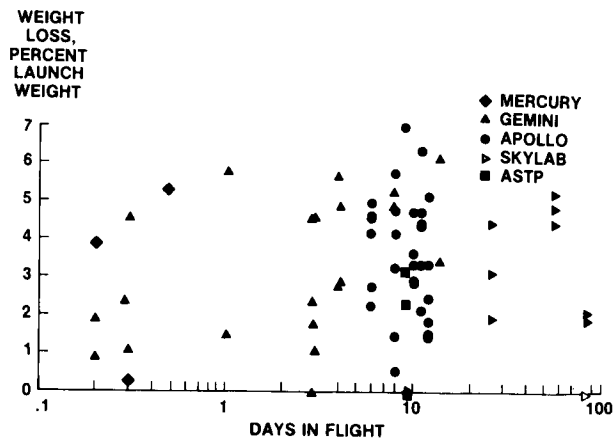


Fig. 3.- Weight losses of all crewmen prior to Shuttle. The loss consists of a 3-4% obligatory loss of fluid plus a variable metabolic loss (or gain). The time scale is logarithmic.

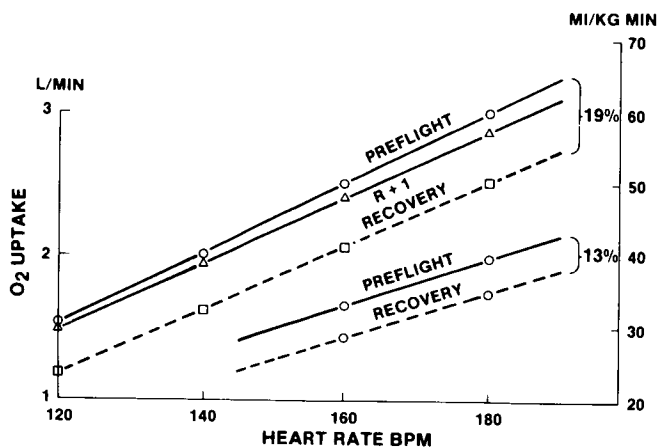


Fig. 4.- Mean of O_2 uptake versus heart rate measured pre- and postflight of Apollo crews. Scale for lower curves is on the right.

Muscle strength and mass are lost (10) as is bone calcium (11, 12). Red cell mass is reduced.

These changes may be understood in terms of three major primary effects of weightlessness:

1. Loss of hydrostatic pressure
2. Loss of locomotor function
3. Alteration of sensory inputs

In addition to these primary effects, there are several less significant ones including changes in size and shape directly caused by absence of weight [Fig. 5] (14), significant changes in height caused by unloading of the intervertebral discs (15) and reduction in girth through loss of weight of abdominal viscera and increase in truncal length.

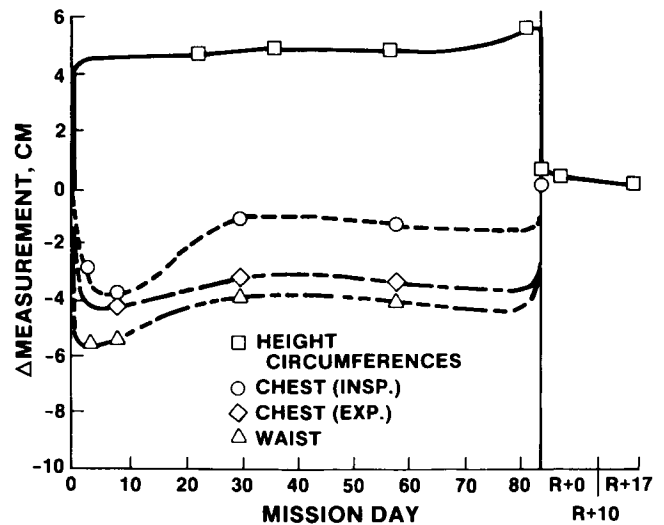


Fig. 5.- Summary of height, chest, and waist girth changes of one crewman on Skylab-4.

Loss of hydrostatic pressure in the vertical blood columns reduces both arterial and venous pressure by some 90 mm Hg at the foot level^b while increasing cephalic arterial pressure by some 30 mm Hg and venous pressure by 8-10 mm. The result of this is an immediate shift of approximately 700 ml. of blood out of the legs (16, 17) which is followed by loss of 2-4 L. of extravascular fluid from the legs over the next several hours [Fig. 6] (14). Sometime over the next 3-5 days

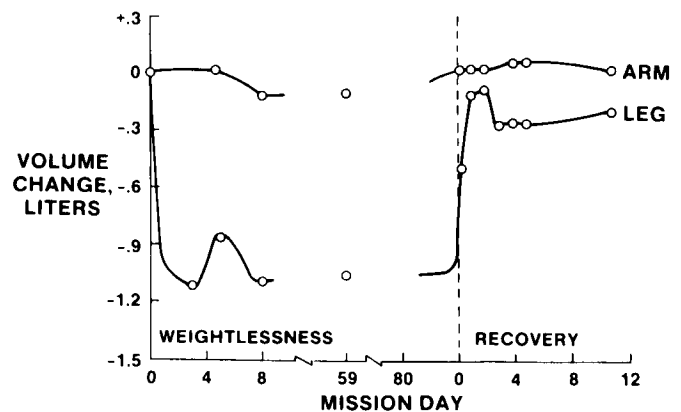


Fig. 6.- Typical volume changes in left leg and arm of Skylab crewman on orbit.

^bThe referenced blood pressures are those when standing in 1-g. As Gauer points out, this is the common posture of man.

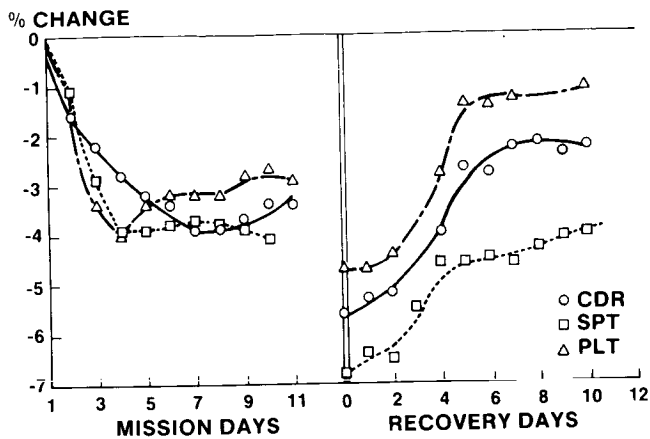


Fig. 7.- Body mass changes during early portion of flight and recovery on Skylab-4. The rapid portion of these changes is believed to represent fluid lost and gained which in these 70 kgm subjects represents approximately 2.5 liters. The absolute difference on recovery represents metabolic losses in flight.

this is lost (18) [Fig 7]. Whether this is by decreased intake or diuresis is, as yet, undetermined. A small portion of it remains as edema in the soft tissues of the head. If the subject remains in weightlessness, the blood volume will be adjusted to the effectively reduced vascular capacity, i.e. approximately 700 ml will be lost over 8-10 weeks (14). On return to 1-g, the major portion of tissue fluid volume is rapidly returned to the legs; and after body water is replenished, there will be an anemia. This redistribution of fluid, at least in part, explains the post-flight orthostasis and reduced exercise tolerance.

The neurological adaptation which has received most attention is Space Motion Sickness, a transient condition affecting some 40+% of first-time subjects in space. Symptoms are sensitivity to angular motion, malaise, lethargy, and infrequent episodic vomiting often without nausea. Etiology appears to be a sensory conflict between the semicircular canals and statolith organ outputs (19). Vomiting is caused by an upper G.I. ileus. We have neither predictive, preventive, nor curative means at this time. Typically after 36 hours, the signs and symptoms rapidly resolve without recurrence. Almost complete resistance to all forms of motion sickness follows for an unknown period of time.

Other sensory adaptations have not been adequately studied. One neuromuscular change produced immediately by weightlessness is the characteristic posture with limb segments in their midposition [Fig 8] (14). This posture is as characteristic as standing, sitting or lying in 1-g. It is of significance only when one attempts to force the body into its 1-g form, such as

sitting in a 1-g chair with a lap belt, or when designing an inflight man machine interface.

A host of other neuromuscular adaptations must occur to avoid overcontrolling, e.g. if anyone ever pushed off with the force of normal walking there would be body damage on contact with the opposite wall. Much less force is required in flight. This makes itself felt during and immediately after entry. Few people leave their seat on the first try after landing. Muscle strength is not significantly reduced in 3-7 days but it is markedly inhibited. This phenomenon has a time constant of several hours, i.e. strength is rapidly returned to normal. There has been considerable comment on lack of sensibility of limb position in flight but this is not sustained by limb position studies I have done.

It is possible that cardiovascular reflexes may also be altered, for a small number of people have symptoms of orthostatic hypotension immediately postflight, yet have normal BP and normal, or slightly low, heart rate for the circumstance.

The reason for this conference is effects of weightlessness on the musculoskeletal and cardiovascular and respiratory systems. At the outset, let us establish one crucial point. Absence of weight does not directly cause the major changes in the musculoskeletal system. If we can bury the term "weight bearing bones," a significant advance will have been made. Absence of weight makes it impossible to walk/run in space. Muscle forces of locomotion are very much larger than body weight. It is the absence of these large inertial loads not absence of weight that cause muscle and bone loss. These forces develop and maintain the heavy bones and muscles of legs and lower trunk. It is also the metabolic loads from such activity that normally determine capacity, condition if you will, of the cardiorespiratory system. On

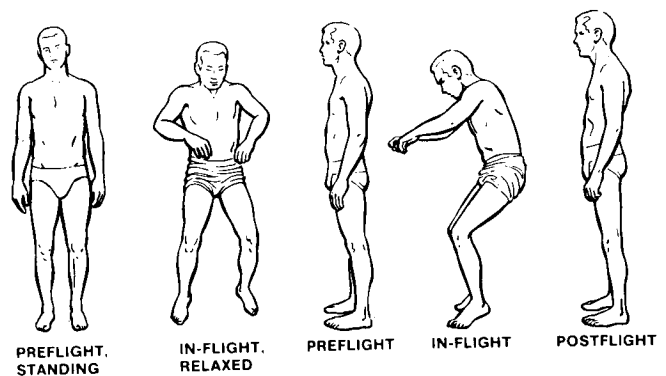


Fig. 8.- One-g and weightless posture compared. In weightlessness, the eyes were closed and body relaxed. This is the natural posture in flight and adjustment to other postures requires either force expenditures by the subject or external restraint.

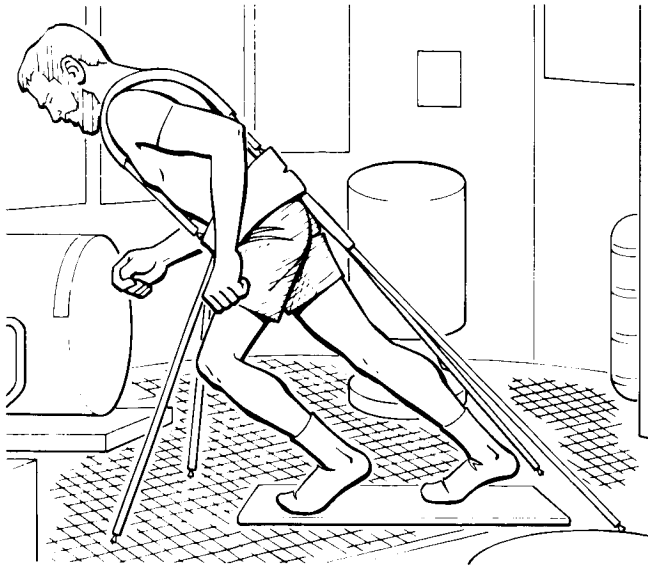


Fig. 9.- Tracing from ciné film on Skylab-4 crewman using crude locomotor exercise device consisting of bungee cords which applied force equivalent to body weight to the subject through hip and shoulder harness and a slippery Teflon plate. It was equivalent to climbing a slippery hill and very fatiguing albeit peak leg forces were probably only slightly above body weight.

Skylab we saw a marked loss of muscle strength and mass on the first two flights which had only bicycle ergometry as leg exercise. There was a sharp reduction in such loss on the longest mission (10), an 84-day flight which had a crude arrangement to allow walking/jumping [Fig 9]. Arms suffered much less loss and this was reduced to negligible amounts by exercise devices. The bicycle ergometer provided adequate cardiorespiratory load to maintain those functions. Ca^{++} was lost on all flights (11) and decreased bone density detected on the last flight (12). Dr. Schneider discusses this in detail in his paper.

Table 1. is a summary of the primary effects, the most prominent changes they produce, and the results of these changes on return to earth. Not shown are the time courses of these changes which occur at different rates and which may vary from individual to individual. Time courses of particular interest to this group will be discussed in more detail in the next section. Crucial to the understanding and dealing with these changes is the recognition that they are normal and appropriate adaptations to weightlessness, and as such, cause no difficulties so long as one remains in space. Some of these changes are incompatible with normal function on earth, i.e. viewed from a reference frame of performance on earth they represent deconditioning. In every case, with the possible exception of trabecular bone loss, they are easily reversible without any residual. It is the purpose of this meeting to decide what and how such adaptations can be prevented by exercise.

Summary - The selection, training, and operations of space flight impose significant physical demands which seem to be adequately met by the existing physical training facilities and informal individual exercise programs. The professional astronaut population has, by selection, a better than average health and physical capacity. The essentials of life on earth are adequately met by the spacecraft, however, the human body adapts to weightlessness which leaves it compromised for the usual life on earth but readaptation is rapid. Long term flight without countermeasures will produce major changes in the cardiovascular, respiratory, musculoskeletal and neuromuscular systems. There is strong theoretical and experimental evidence from 1-g studies and limited in-flight evidence to believe that exercise is a key countermeasure to many of these adaptations.

Table 1

Summary of changes produced by the major primary effects of weightlessness and effects seen on return to earth. The changes inflight are correlated to the effects seen on return to earth by their numerals.

Primary Effects of Weightlessness	Effects on Return to Earth	
<i>Removal of Hydrostatic Pressures</i>		
1. Shift and Loss of Blood Volume*	● Reduced weight ^a	1,2,7
2. Shift and Loss of Extra-vascular fluid	● Orthostasis	1,2,9(?)
	● Reduced exercise capacity	1,2,3,5,6
<i>Loss of Locomotor Function</i>		
Reduced Force Loads		
3. Muscle Atrophy*	● Reduced strength	3,8
4. Bone Loss*	● Reduced skeletal integrity	4
Reduced Metabolic Loads		
5. Decreased Cardiovascular capacity*	● Reduced work capacity	
6. Decreased Cardiorespiratory capacity*		
<i>Altered Neurological Inputs</i>		
7. Space Motion Sickness	● Altered postural and locomotor stability	3,8(?), 10(?)
8. Change in proprioceptive set points*	● Increased resistance to motion sickness	10
9. ?Change in baroreceptor set points?		
10. Changes in vestibular system		

^aThis is an obligatory fluid loss, majority of losses have an added metabolic loss (or gain) which is avoidable.

*Potential for modification by exercise.

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